

# Quarkonium as a tool: cold nuclear matter effects

E. G. Ferreira<sup>a</sup>, F. Fleuret<sup>b</sup>, J.P. Lansberg<sup>c</sup>, N. Matagne<sup>d</sup>, A. Rakotozafindrabe<sup>e</sup>

<sup>a</sup>Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, E-15782 Santiago de Compostela, Spain

<sup>b</sup>LLR, École polytechnique, CNRS, F-91128 Palaiseau, France

<sup>c</sup>IPNO, Université Paris-Sud 11, CNRS/IN2P3, F-91406 Orsay, France

<sup>d</sup>Université de Mons, Service de Physique Nucléaire et Subnucléaire, Place du Parc 20, B-7000 Mons, Belgium

<sup>e</sup>IRFU/SPH, CEA Saclay, F-91191 Gif-sur-Yvette Cedex, France

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## Abstract

We discuss the quarkonium production as a tool for the study of the Quark Gluon Plasma. In particular, we concentrate on the Cold Nuclear Matter effects. We show that quarkonium production is also useful for the study of Quantum Chromodynamics first principles and the nuclear Parton Distribution Functions.

**Keywords:** Quarkonium, Shadowing, Cold Nuclear Matter effects

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## 1. Introduction

The interest devoted to quarkonium production has not decreased for the last thirty years. It is motivated by the search of the transition from hadronic matter to a deconfined state of matter, the so-called Quark-Gluon Plasma (QGP). The high density of gluons in the QGP is expected to hinder the formation of quarkonium systems, by a process analogous to Debye screening of the electromagnetic field in a plasma [1].

Nevertheless, the BNL Relativistic Heavy Ion Collider data on  $d+Au$  collisions [2] have also revealed that Cold Nuclear Matter (CNM) effects play an essential role at these energies.

All this confirms that, in fact, the interpretation of the results obtained in nucleus-nucleus collisions relies on a good understanding and a proper subtraction of the CNM effects, known to impact the quarkonium production in proton(deuteron)-nucleus collisions where the deconfinement can not be reached.

We will focus on  $d+Au$  data, where no QGP formation is possible and only CNM effects are in play. Two CNM effects have been identified as important for quarkonium production: the nuclear absorption, commonly characterized as a final-state effect on the produced quarkonium state and parametrised through an effective breakup cross section, and the shadowing, *i.e.* the modification of the parton densities in nuclei relative to the nucleon, an initial-state effect.

Moreover, we have recently realized that the theoretical uncertainty on the shadowing is not limited to the

uncertainty on the modification of the parton distributions: we do not know the specific production kinematics at a partonic level, this prevents us to know the exact momentum fractions of the gluon in the nucleus and thus at which  $x_B$  to evaluate it.

In this work, we illustrate the importance of cold matter effects on  $J/\psi$  production in  $pPb$  and  $PbPb$  collisions at the LHC and we recall that a proper subtraction of CNM effects on quarkonium production is mandatory before any QGP studies at the LHC.

## 2. Our approach

As we have shown in earlier studies [3, 4, 5, 6], considering the adequate  $J/\psi$  partonic production mechanism – either via a  $2 \rightarrow 1$  or a  $2 \rightarrow 2$  process – affects the way to compute the nuclear shadowing and thus its expected impact on the  $J/\psi$  production. In the following, we will refer to the first scenario as the *intrinsic* scheme, and to the second as the *extrinsic* scheme. Most studies on the  $J/\psi$  production in hadronic collisions are carried out in the intrinsic scheme. They rely on the assumption that the  $c\bar{c}$  pair is produced by the fusion of two gluons carrying some intrinsic transverse momentum  $k_T$ . The partonic process being a  $2 \rightarrow 1$  scattering, the sum of the gluon intrinsic  $k_T$  is transferred to the  $c\bar{c}$  pair, thus to the  $J/\psi$  since the soft hadronisation process does not alter significantly the kinematics. Thus, in such approaches, the transverse momentum  $P_T$  of the  $J/\psi$  *entirely* comes from the intrinsic  $k_T$  of the initial

gluons. However, the average value of  $k_T$  is not expected to go much beyond  $\sim 1$  GeV. So this process is not sufficient to describe the  $P_T$  spectrum of quarkonia in hadron collisions [7].

For  $P_T \gtrsim 2 - 3$  GeV, most of the transverse momentum of the quarkonia should have an extrinsic origin, *i.e.* the  $J/\psi$ 's  $P_T$  would be balanced by the emission of a recoiling particle in the final state. The  $J/\psi$  would then be produced by gluon fusion in a  $2 \rightarrow 2$  partonic process with the emission of a hard final-state gluon. This emission, which is anyhow mandatory to conserve  $C$ -parity, has a definite influence on the kinematics of the  $J/\psi$  production. Indeed, for a given  $J/\psi$  momentum (thus for fixed rapidity  $y$  and  $P_T$ ), the processes discussed above, *i.e.* the intrinsic  $g + g \rightarrow c\bar{c} \rightarrow J/\psi (+X)$  and the extrinsic  $g + g \rightarrow J/\psi + g$ , will proceed on the average from initial gluons with different Bjorken- $x$ . Therefore, they will be affected by different shadowing corrections.

In the intrinsic scheme, the measurement of the  $J/\psi$  momentum in  $pp$  collisions completely fixes the longitudinal momentum fraction of the initial partons:

$$x_{1,2} = \frac{m_T}{\sqrt{s_{NN}}} \exp(\pm y) \equiv x_{1,2}^0(y, P_T), \quad (1)$$

with  $m_T = \sqrt{M^2 + P_T^2}$ ,  $M$  being the  $J/\psi$  mass.

However, in the extrinsic scheme, the knowledge of the  $y$  and  $P_T$  spectra is not sufficient to determine  $x_1$  and  $x_2$ . Actually, the presence of a final-state gluon introduces further degrees of freedom in the kinematics, allowing several  $(x_1, x_2)$  for a given set  $(y, P_T)$ . The four-momentum conservation explicitly results in a more complex expression of  $x_2$  as a function of  $(x_1, y, P_T)$ :

$$x_2 = \frac{x_1 m_T \sqrt{s_{NN}} e^{-y} - M^2}{\sqrt{s_{NN}} (\sqrt{s_{NN}} x_1 - m_T e^y)}. \quad (2)$$

Equivalently, a similar expression can be written for  $x_1$  as a function of  $(x_2, y, P_T)$ . Even if the kinematics determines the physical phase space, models are anyhow *mandatory* to compute the proper weighting of each kinematically allowed  $(x_1, x_2)$ . This weight is simply the differential cross section at the partonic level times the gluon PDFs, *i.e.*  $g(x_1, \mu_F)g(x_2, \mu_F) d\sigma_{gg \rightarrow J/\psi+g}/dy dP_T dx_1 dx_2$ . In the present implementation of our code, we are able to use the partonic differential cross section computed from *any* theoretical approach. In this work, we shall use the Colour-Singlet Model (CSM) at LO at LHC energy, which was shown to be compatible [8, 9] –see Fig. 1 for illustration– with the magnitude of the  $P_T$ -integrated cross-section as given by the PHENIX  $pp$  data [10],

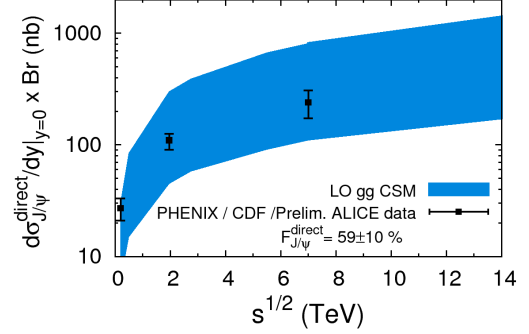


Figure 1:  $d\sigma_{J/\psi}^{\text{direct}}/dy|_{y=0} \times \text{Br}$  from  $gg$  fusion in  $pp$  collisions for  $\sqrt{s}$  from 200 GeV up to 14 TeV compared to the PHENIX [10], CDF [11] and ALICE data.

the CDF  $p\bar{p}$  data [11] and the recent LHC  $pp$  data at  $\sqrt{s_{NN}} = 7$  TeV.

To obtain the yield of  $J/\psi$  and  $\Upsilon$  in  $pA$  and  $AA$  collisions, a shadowing-correction factor has to be applied to the  $J/\psi$  yield obtained from the simple superposition of the equivalent number of  $pp$  collisions. This shadowing factor can be expressed in terms of the ratios  $R_i^A$  of the nuclear Parton Distribution Functions (nPDF) in a nucleon belonging to a nucleus  $A$  to the PDF in the free nucleon:

$$R_i^A(x, Q^2) = \frac{f_i^A(x, Q^2)}{A f_i^{\text{nucleon}}(x, Q^2)}, \quad i = q, \bar{q}, g. \quad (3)$$

The numerical parameterisation of  $R_i^A(x, Q^2)$  is given for all parton flavours. Here, we restrict our study to gluons since, at high energy, the quarkonia are essentially produced through gluon fusion [7]. Several shadowing parametrisations are available [12, 13, 14, 15]. In the following, we shall restrict ourselves to EKS98 [13], which is very close to the mean in the current evaluation of the uncertainty [15] on the gluon nPDF and exhibit a moderate antishadowing.

The second CNM effect that we take into account concerns the nuclear absorption. In the framework of the probabilistic Glauber model, this effect is usually parametrised by introducing an effective absorption cross section  $\sigma_{\text{abs}}$ . It reflects the break-up of correlated  $c\bar{c}$  pairs due to inelastic scattering with the remaining nucleons from the incident cold nucleus. The value of  $\sigma_{\text{abs}}$  is unknown at the LHC. At high energy, the heavy state in the projectile should undergo a coherent scattering off the nucleons of the target nucleus [16], in contrast to the incoherent, longitudinally ordered scattering that takes place at low energies. As argued in [17, 18], this should lead to a decrease of  $\sigma_{\text{abs}}$  with increasing

$\sqrt{s_{NN}}$ . Compilation and systematic study of many experimental data indicate that  $\sigma_{\text{abs}}$  appears either constant [19] or decreasing [20] with energy. Hence, we can consider our estimates [5, 6] of  $\sigma_{\text{abs}}$  at RHIC energy as upper bounds for the value of  $\sigma_{\text{abs}}$  at the LHC. We choose three values of the absorption cross section that should span this interval ( $\sigma_{\text{abs}} = 0, 1.5, 2.8$  mb).

### 3. Results

In the following, we present our results for the  $J/\psi$  nuclear modification factor due to CNM effects in the extrinsic scheme in  $p\text{Pb}$  and  $\text{PbPb}$  collisions at  $\sqrt{s_{NN}} = 5.5$  TeV:  $R_{AB} = dN_{AB}^{J/\psi} / \langle N_{\text{coll}} \rangle dN_{pp}^{J/\psi}$ , where  $dN_{AB}^{J/\psi}$  ( $dN_{pp}^{J/\psi}$ ) is the observed  $J/\psi$  yield in  $AB = p\text{Pb}, \text{PbPb}$  ( $pp$ ) collisions and  $\langle N_{\text{coll}} \rangle$  is the average number of nucleon-nucleon collisions occurring in one  $p\text{Pb}$  or  $\text{PbPb}$  collision. Without nuclear effects,  $R_{AB}$  should equal unity.

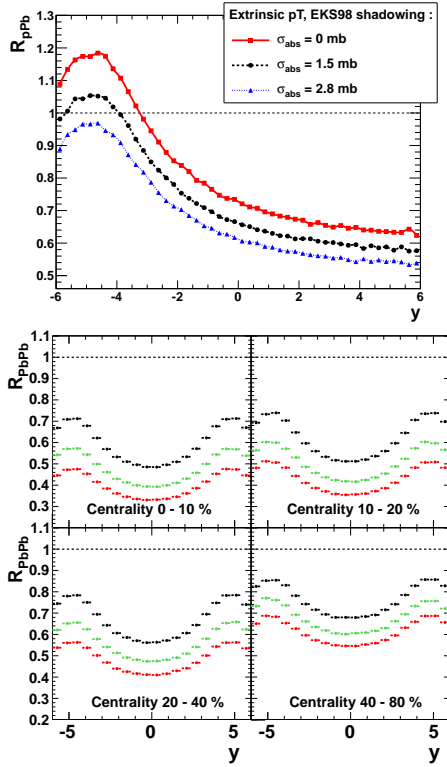


Figure 2:  $J/\psi$  nuclear modification factor versus  $y$  in  $p\text{Pb}$  and  $\text{PbPb}$  collisions at  $\sqrt{s_{NN}} = 5.5$  TeV, using EKS98 [13] gluon shadowing parametrisation and three values of  $\sigma_{\text{abs}}$  (from top to bottom: 0, 1.5, 2.8 mb) in the extrinsic scheme. For  $\text{PbPb}$  collisions, the  $y$ -dependence is shown for various centrality selections.

In Fig. 2, we show  $R_{p\text{Pb}}$  versus  $y$ . The curve with no absorption allows us to highlight the strong rapidity

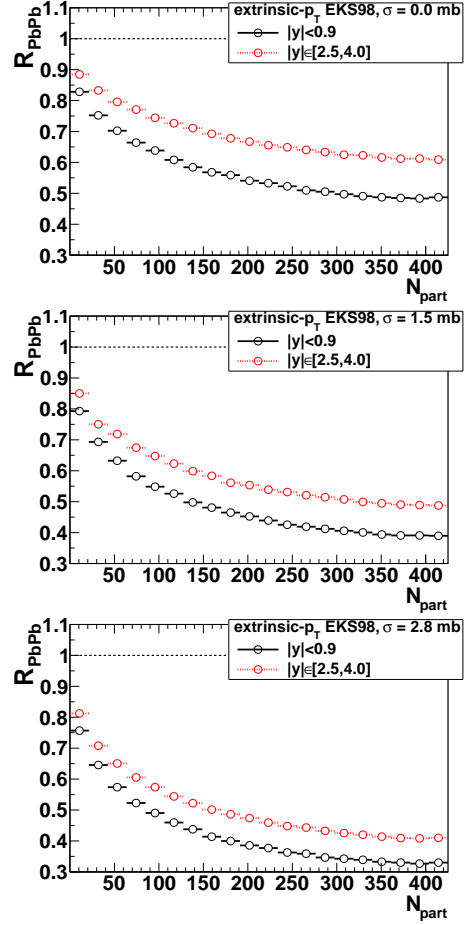


Figure 3: (Color online)  $J/\psi$  nuclear modification factor,  $R_{\text{PbPb}}$ , in  $\text{PbPb}$  collisions at  $\sqrt{s_{NN}} = 5.5$  TeV versus  $N_{\text{part}}$ , using EKS98 [13] gluon shadowing parametrisation and three values of the nuclear absorption cross section in the extrinsic scheme.  $R_{\text{PbPb}}$  is shown for two different experimental acceptances in rapidity,  $|y| < 0.9$  and  $|y| \in [2.5, 4]$ .

dependence of the shadowing. We can also notice that the shadowing alone should already be responsible for a quite large amount of  $J/\psi$  suppression, up to 36 % at  $y = 6$ . This is expected because one accesses at LHC energy the region of very small  $x$  in the gluon nPDF (down to  $10^{-5}$ ). At backward rapidity, we are in the antishadowing region, with the antishadowing peak at  $y \simeq -5$ . Fig. 2 shows that the  $y$ -dependence of  $R_{\text{PbPb}}$  for the centrality bins used by the ATLAS Collaboration [21] is similar for all the bins, with a dip at mid- $y$ . This shape is the opposite of the one obtained at RHIC energy [3, 5], with a peak at mid- $y$ . One can also notice that  $R_{\text{PbPb}}$  decreases at very large rapidity showing that one has gone beyond the antishadowing peak. Here,  $R_{\text{PbPb}}$  is systematically smaller at mid- $y$  than at forward- $y$ . This is also illustrated on Fig. 3, with the centrality dependence of

$R_{\text{pPb}}$  for two regions in  $y$ . This behaviour of the CNM effects may partially – or completely – compensate the opposite effect expected from  $c\bar{c}$  recombination, with a maximum enhancement at  $y = 0$ . We should however note that the recombination of  $c\bar{c}$  pairs is expected to be less important if an experimental  $P_T$  cut has to be imposed because of a limited acceptance at low  $P_T$ . Overall, one may observe a  $R_{\text{pPb}}$  rather independent of  $y$  resulting of two  $y$ -dependent effects.

Recently, we have also paid attention to the preliminary data on  $\Upsilon$  production at RHIC. In Fig. 4, we show  $R_{dAu}$  vs  $y$  according to the extrinsic scheme. The results are displayed for 3 values of  $\sigma_{\text{abs}}$  and for three shadowing parametrisations and these are compared to the available RHIC data [22, 23].

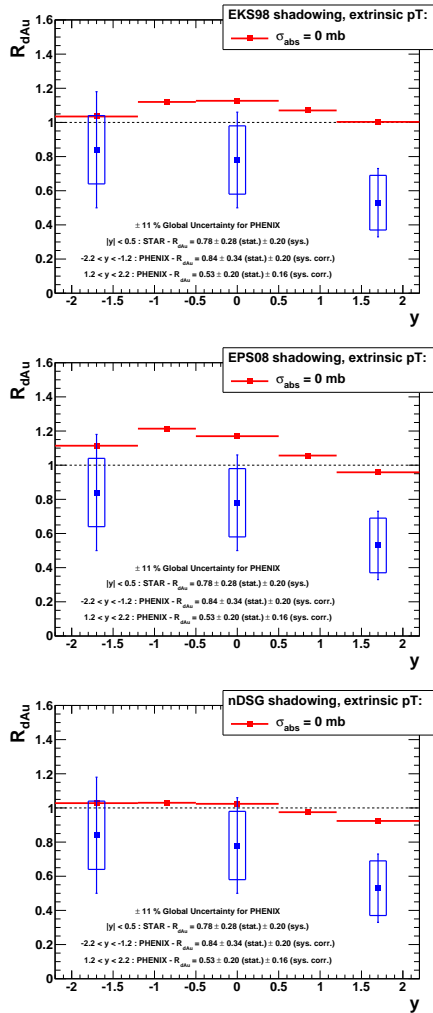


Figure 4:  $\Upsilon$  nuclear modification factor in  $dAu$  collisions at  $\sqrt{s_{NN}} = 200$  GeV versus  $y$  using the following gluon shadowing parametrisations: a) EKS98, b) EPS08, c) nDSG

#### 4. Conclusions

In conclusion, we know from lattice QCD that strongly interacting matter undergoes a deconfinement transition to a new state, the QGP. The objective of high energy nuclear collisions is to produce and study the QGP under controlled conditions in the laboratory. The study of quarkonium production and suppression is among the most interesting investigations in this field since calculations indicate that the QCD binding potential is screened in the QGP phase. As demonstrated in this work, other phenomena will also impact on the quarkonium production rates in nuclear collisions at the LHC. For instance, nuclear parton distributions modifications and CNM absorption of quarkonium must be accounted for before any QGP studies at the LHC become meaningful. E.G.F. thanks Xunta de Galicia and Ministerio de Ciencia of Spain (FPA2008-03961-E/IN2P3), N.M. thanks the F.R.S.-FNRS (Belgium).

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